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Ultra-high-efficiency L-band erbium-doped superfluorescent fiber source with broadening linewidth

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Abstract. We investigate a high-pumping-efficiency and linewidth-broadening, L-band, erbium-doped, superfluorescent fiber source (SFS) using a cascaded dual-backward-pumped configuration. With optimized structural parameters, the design provides an L-band SFS with a mean wavelength of 1578.2 nm, an output power of 132.8 mW, and a spectral linewidth of 52.6 nm without using any external spectral filters under 265-mW pump power. The high pumping efficiency of 50.1% is achieved experimentally. The design relaxes the danger in resonant lasing while enhancing the pumping efficiency and broadening the linewidth. [DOI: 10.1117/1.3481119]

Subject terms: fiber optics amplifiers and oscillators; superfluorescent fiber source; erbium-doped fiber; fiber optic gyroscope.

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1 Introduction

Incoherent broadband amplified spontaneous emission (ASE) optical sources at 1.55 μm have been widely considered as the light sources for dense wavelength-division-multiplexing (DWDM) device characterization, spectrum-sliced DWDM systems,[1,2] and fiber-optic gyroscopes.[3] The erbium-doped fiber (EDF) based superfluorescent fiber source (SFS) is a good candidate for simultaneously offering a broad spectral linewidth, high output power, and an excellent mean wavelength stability to meet application requirements. There are four general kinds of configurations to implement ASE sources: single-pass forward (SPF), single-pass backward (SPB), double-pass forward (DPF), and double-pass backward (DPB). Among them, the DPB configuration has demonstrated the highest output power, best mean wavelength stability, and broadest linewidth for C-band (1525 to 1565 nm) SFS.[4] However, to generate an L-band (1565 to 1605 nm) SFS, only the DPF configuration is satisfactory; other configurations are intrinsically difficult to serve as an L-band ASE source for applications.[5,6] The output spectra of the DPB and SPB configurations always have a main hump at ~1560 nm, regardless of the EDF length. Although the SPF configuration can achieve an L-band spectrum using a proper EDF length, the output power is too small for most applications. Such results are significantly different compared with their corresponding C-band counterparts. The SFS that operates in the L-band has recently become an interesting research topic because of the fiber-optic communication window's expansion to the L-band.

Although it is intrinsically hard to generate an L-band SFS with the DPB configuration, we present in this paper a demonstration of the cascaded dual-backward-pumped configuration's success in generating an L-band SFS. The pumping conversion efficiency of such an L-band SFS is very high, and the spectral linewidth is significantly broadened. The high output power and wide spectral linewidth with small power ripple are obtained without using any external spectral filters. The experiment also shows that the proposed configuration relaxes the danger in resonant lasing. We found that the cascaded dual-backward-pumped configuration was the best at generating a higher-pumping-efficiency L-band SFS with broader linewidth compared with that by the dual-forward-pumped configuration[7] and the bidirectional-pumped configuration.[8]

2 Configuration of the Proposed L-Band SFS

Figure 1 shows the proposed configuration of the dual-backward-pumped L-band SFS. The designed source consists of two pieces of conventional erbium-doped fibers (EDF1 and EDF2), two 1480/1590-nm-wavelength selective couplers (WDM1, WDM2), two 1480-nm pump laser diodes (LD1, LD2), an end fiber loop mirror (FLM) used to reflect the ASE light to form a double-pass configuration, and an optical isolator (ISO) at the output port. Obviously the design is a cascaded dual-backward-pumped configuration. We define the total length of the EDF as $L=L_1+L_2$, where L_1 and L_2 refer to the first-stage (EDF1) and second-stage (EDF2) lengths, respectively. The fiber length ratio of the EDF1 length to the total length is defined as R_L

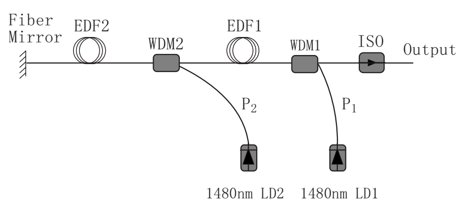

Fig. 1 Proposed cascaded dual-backward-pumped L-band SFS configuration.

$=L_1/(L_1+L_2)$. Similarly, the pump ratio is defined as the pump power of the first stage to the total pump power, i.e., $R_p=P_1/(P_1+P_2)$. The EDF used in both simulations and experiments is Lucent Technologies' heavily doped LRL fiber (type number L12403),[9] with a peak absorption of 27 to 33 dB/m at 1530 nm, mode field radius of 5.2 μm, cutoff wavelength of 1100 to 1400 nm, and numerical aperture of 0.25.

It has been proved that the L-band ASE is realized through a longer EDF.[5,6] The principle of the L-band SFS proposed here can be explained as follows: The C-band ASE generated by the anterior fiber is injected into the later fiber to be a second pump source, and the L-band ASE will be achieved in the output. For the configuration presented in this paper, the C-band output of EDF2 was transfused into EDF1 to be a second pump source. As a result, the L-band output spectrum was obtained in the output end of the EDF1 with an appropriate fiber length arrangement and pump ratio. The pump power P_1 and EDF1 work together to amplify the L-band spectrum. Because the 1550-nm ASE generated by the 1480-nm pumping is the pump source for the 1580-nm band, the amplification and the quantum conversion efficiency to 1580-nm ASE with the 1480-nm band pumping is higher than that with the 980-nm pumping. Therefore, the 1480-nm pumping is considered in this configuration.

3 Results and Discussion

To obtain the optimal parameters of this configuration and gain the best output properties, the commercial amplifier simulation package OASIX was used to perform the simulations of the proposed configuration.[10] The rate equations and power evolution equations in Ref. 3 were adopted for the simulations, which were completed by the simulation package. In the equations, the pump and signal excited-state absorption (ESA) from the pump state or from the upper-laser state were neglected because the cross-sections for these processes were small or the occupation of the absorbing state was negligible, i.e., a 1480-nm pump band was considered to be free from ESA.[3] As is well known, the gain in the longer wavelength range of the L-band was degraded due to the $^4I_{13/3}\rightarrow{}^4I_{9/2}$ ESA that appears from 1620 nm. It was previously proved that the simulation software we used is accurate and effective for characterizing SFS and presenting the same results as those obtained by experiments.[11–13]

Previous simulations and experiments indicated that the wavelength range of the output ASE spectrum was largely dependent on the total fiber length used. Therefore, the total EDF length L was initially optimized to obtain a flat L-band spectrum output. The effective FLM reflectivity was selected to be 90%. The output spectral linewidth of the L-band SFS against the total EDF lengths at different L_2 (2, 5, 8, and 11 m) were simulated. The pump powers of the two stages were both set at 80 mW. The results indicate that the optimal EDF length to obtain the widest linewidth of the L-band SFS at different L_2 were all approximately 20 m, as shown in Fig. 2. The results of other pump power ratio simulations also show that the widest linewidth occurred at an EDF length of 20 m. The widest spectral linewidth means that the lowest spectrum ripple is the flattest of the L-band spectrum. Hence, in the subsequent simulations, the total EDF length was fixed at 20 m of the proposed cascaded dual-backward-pumped L-band SFS.

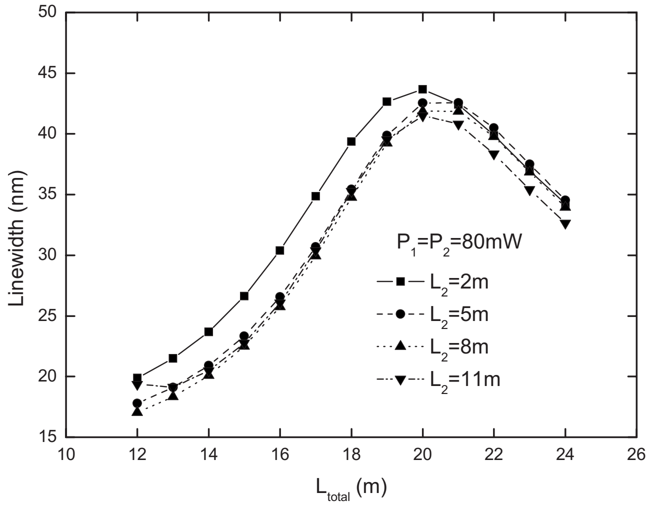

Fig. 2 Spectral linewidth versus total EDF length.

Figure 3 shows that the output ASE spectra under different R_L with the pump powers of the two stages were both set at 80 mW. The proposed configuration became a DPB configuration when $R_L=0$, which did not generate a flat L-band SFS. The output spectrum is shown as cover (a) in Fig. 3. When the cascaded dual-backward-pumped configuration was used (i.e., $R_L=0.1,0.5,0.8$), the configuration successfully generated a flat L-band SFS, shown as cover (b) to (d) in Fig. 3. In particular, the cascaded dual-backward-pumped configuration generated a linewidth broadening L-band SFS in the case of $R_L=0.1$. The linewidth was over 15 nm broader than that of the conventional L-band SFS.

The effects of the fiber length ratio R_L and pump ratio R_p on the output spectrum were addressed to gain insight into the properties of the dual-backward-pumped L-band SFS. At a set of pump power allotments R_p at a fixed 160-mW total pump power, the output characteristics were simulated

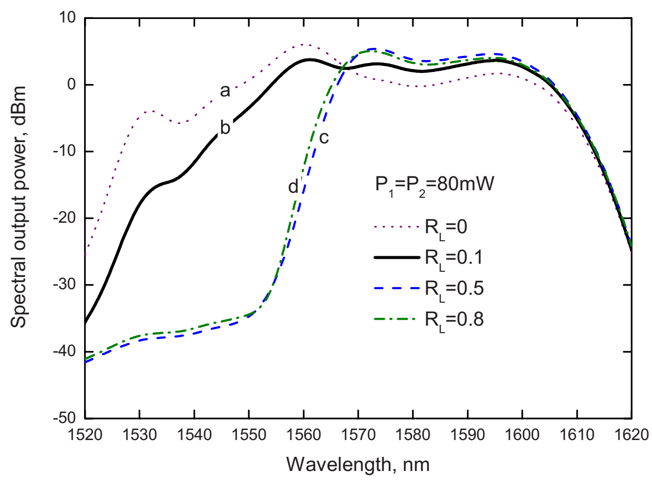

Fig. 3 Simulated output ASE spectra with different R_L.

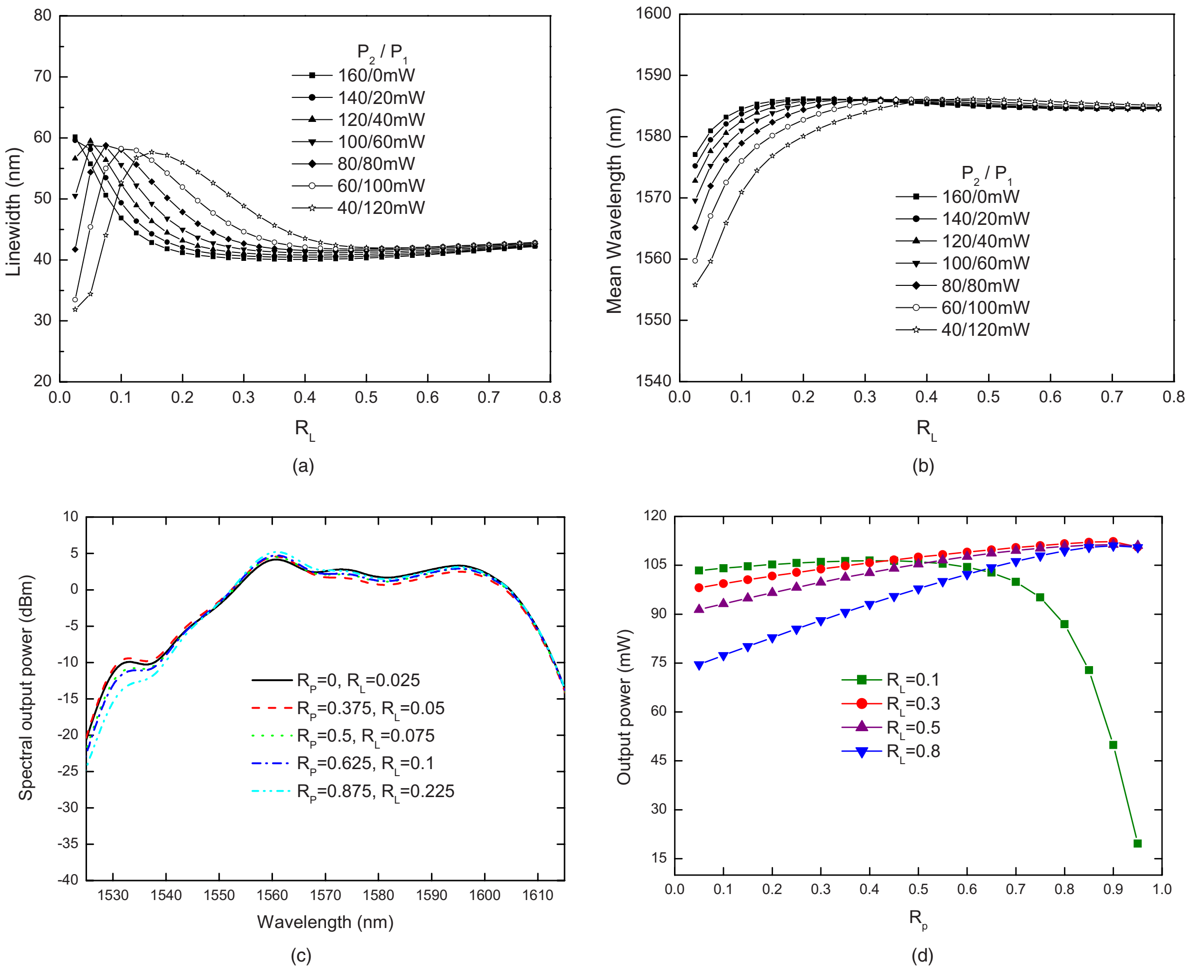

Fig. 4 (a) Calculated linewidth. (b) Mean wavelength versus R_L in the seven given pump power allotments. (c) Flattest output spectra at different pump ratios. (d) Output power versus pump ratio at four different fiber length ratios.

in terms of linewidth, mean wavelength, and output power of the L-band SFS on R_L. The calculated linewidth and mean wavelength of the L-band SFS versus R_L are given in Figs. 4(a) and 4(b), respectively. Figures 4(a) and 4(b) show that when the proportion of the fiber length L_1 for stage 1 is larger than 0.5, the fiber length ratio and pump ratio had little inference on the linewidth and mean wavelength. The output spectrum was a conventional L-band SFS with a linewidth around 42 nm. Thus, the cascaded dual-backward-pumped configuration can only provide a conventional L-band SFS in the condition of $R_L > 0.5$. However, Fig. 4(a) shows that the proposed cascaded dual-backward-pumped configuration provided an L-band SFS with significant linewidth broadening at a specific fiber length ratio below 0.25 for all the cases of pump power allotments. The output spectra with the maximum linewidth set at different pump ratios (i.e., $R_p = 0, 0.375, 0.5, 0.625, 0.875$) are shown in Fig. 4(c) with each the fiber length ratio optimized. Figure 4(c) shows that the output spectra all fall on the L-band to some extent up to the edge of the C-band, thus inducing a linewidth broadening of about 60 nm. The proposed cascaded dual-backward-pumped configuration can always achieve an L-band SFS with a broadening linewidth at various kinds of pump ratios by optimizing the fiber length ratio. The pump ratio and fiber length ratio affect the output power as well. Figure 4(d) illustrates the output power versus pump ratio at four different fiber length ratios (i.e., $R_L = 0.1, 0.3, 0.5, 0.8$). For the cases of $R_L = 0.3$, 0.5, and 0.8, the output power increased with the pump ratio, and their available maximum output power were all achieved with the pump ratio around 0.875. But for $R_L = 0.1$, the output power remained almost constant with the pump ratio between 0 and 0.5. The output power dropped quickly when the pump ratio was larger than 0.5.

To choose the best fiber length ratio and pump ratio of the proposed configuration, Fig. 5(a) illustrates the maximum available linewidth at different pump ratios by optimizing the fiber length ratio, and their corresponding output power and mean wavelength. Figure 5(a) shows that the dual-backward-pumped configuration successfully implemented an L-band SFS with various pump ratios. By optimizing the fiber length ratio at different pump ratios, the L-band SFS with linewidth broadening over 55 nm can always be achieved. The broadest linewidth of 60.1 nm was achieved at a pump ratio of 0, i.e., $P_1 = 0$, $P_2 = 160$ mW. For the other criteria, Fig. 5(b) illustrates the available maximum output power at different pump ratios by optimizing

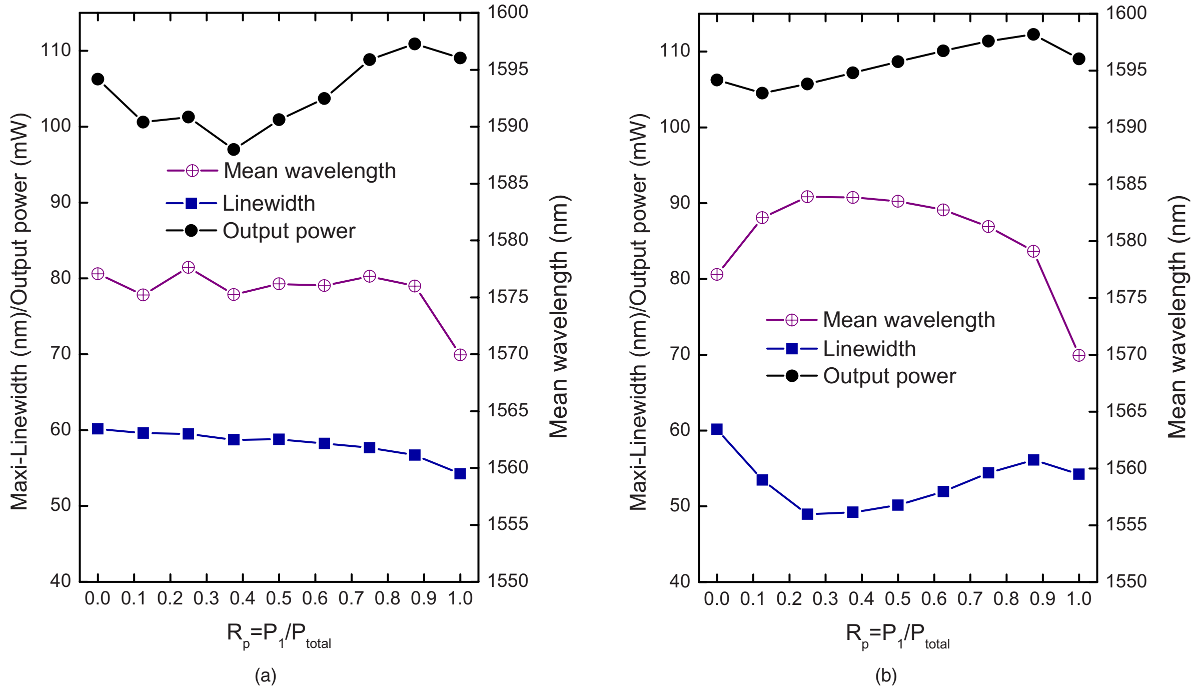

Fig. 5 (a) Calculated maximum linewidth by optimizing the fiber length ratio, corresponding output power, and mean wavelength versus R_P. (b) Calculated maximum output power by optimizing the fiber length ratio, corresponding linewidth, and mean wavelength versus R_P.

the fiber length ratio, and their corresponding linewidth and mean wavelength. Figure 5(b) shows that the highest output power occurred at R_P=0.875, corresponding to a theoretical pump efficiency of 70.1%. When R_P=0.875, the dual-backward-pumped design also provided quite a broad spectral linewidth of 56.1 nm. Figures 5(a) and 5(b) demonstrate that the proposed design can provide a good L-band SFS in two cases, i.e., R_P=0 and R_P=0.875.

A more detailed comparison of the two cases was carried out and is described in the following. Figure 6(a) illustrates the linewidth and output power versus fiber length ratio with pump ratios of 0 and 0.875. The broadest linewidths of 60.1 nm at R_L=0.025 and 56.7 nm at R_L=0.225 were achieved for pump ratios of 0 and 0.875, respectively. In the case of R_P=0.875 the output power remained almost constant with a large R_L range between 0.2 and 0.85. In the case of R_P=0, the output power decreased monotonously with R_L. Figure 6(b) illustrates the linewidth and output power versus total pump power with optimized fiber length ratios. The results show that the characteristics of linewidth

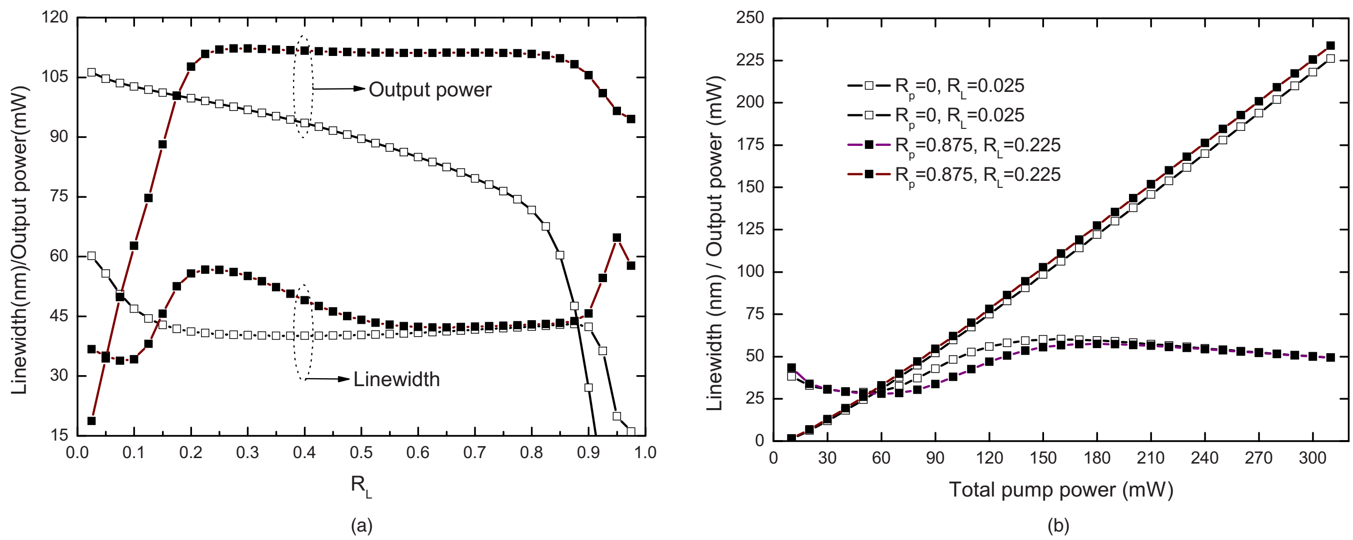

Fig. 6 (a) Calculated linewidth and output power versus fiber length ratio. (b) Calculated linewidth and output power versus total pump power with optimized fiber length ratio. White squares represent the data for R_P=0, and black squares represent the data for R_P=0.875.

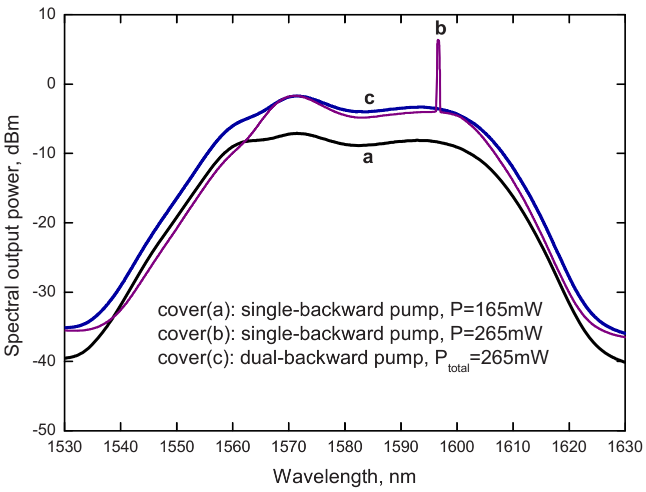

Fig. 7 Output spectra of the single-backward and dual-backward pump configurations.

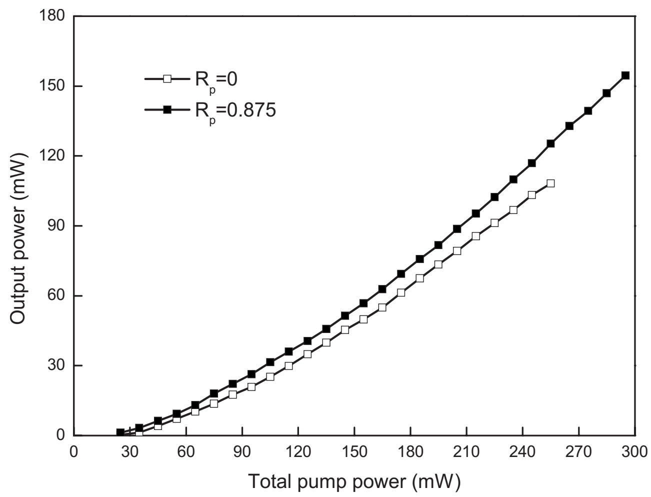

Fig. 8 Output powers versus pump power of the SFS with $R_P=0$ and 0.875.

and output power with $R_P=0$ are comparable to those of $R_P=0.875$. However, the configuration is simpler and more practical for $R_P=0$ since it requires only one pump.

Based on the above simulation results, the output characteristics of the L-band SFS with two different R_P ($R_P=0, 0.875$) were compared experimentally. For the first experiment on the single-backward-pumped L-band SFS, i.e., $R_P=0$, the R_L was selected as 0.025 based on the simulation, i.e., the fiber length of the first stage (unpumped fiber) was 0.5 m and the length of the second stage (backward-pumped fiber) was chosen to be 19.5 m. In the experiment, the output power and the spectrum were measured, respectively, using an optical power meter and an optical spectrum analyzer with a resolution of 0.02 nm. The spectra of the single-backward-pumped L-band SFS under the two pump powers of 165 and 265 mW are shown as covers (a) and (b) in Fig. 7, respectively. The output spectrum with 165-mW pump power was recorded because it was the flattest and fell in the L-band. A flat L-band spectrum was achieved with a 54.2-nm bandwidth, which is obviously broader than that of the conventional L-band spectrum using the DPF configuration. With an additional increase in the pump power, the output power would increase as well, but the output spectrum would get a little worse (not as flat as under 165 mW). Most important, the laser occurred when the pump power was increased to 265 mW, which induced the narrower linewidth shown as cover (b) in Fig. 7. Thus, a high-output-power operation with high pumping efficiency for the single-backward-pumped L-band SFS configuration is difficult to realize since it is inhibited by the instantaneous resonant lasing effect.

For our second experiment on the cascaded dual-backward-pumped L-band SFS, i.e., $R_P=0.875$, R_L was selected as 0.225 ($L_1=4.5$ m, $L_2=15.5$ m) based on the simulation. The output spectrum was observed, and no lasing occurred when the pump power was increased to 300 mW. The flattest L-band spectrum is recorded as cover (c) in Fig. 7 under 265-mW pump power. The output L-band SFS had an output power of 132.8 mW, a spectral linewidth of 52.6 nm, and a mean wavelength of 1578.2 nm. A high pumping efficiency of 50.1% was achieved.

Figure 8 illustrates the output power versus pump power of the two SFSs. The results show that the pumping efficiency of the L-band SFS by the cascaded dual-backward-pumped configuration was a little higher than that of the single-backward-pumped configuration, i.e., $R_P=0$. Further, the experiment on the dual-backward-pumped configuration shows that it relaxed the danger in resonant lasing when the pump power was more than 265 mW, thus allowing a higher-pumping-power operation and therefore enhancing the pumping efficiency. The cascaded dual-backward-pumped configuration was better than the single-backward-pumped configuration for generating a higher-output-power L-band SFS. The experimental results are qualitatively in good agreement with the simulations. The trends of efficiency enhancement and linewidth broadening by optimizing the R_L ratio in the single-backward-pumped configuration and the R_p and R_L ratios in the cascaded dual-backward-pumped configuration are basically the same between the experimental results and the simulations. The discrepancies in the pumping efficiency of the L-band SFSs between the experiment and simulation are mainly due to the splicing loss between the EDF and the single-mode fiber (SMF), and the components losses in the experiment, which were not taken into account in the simulation.

Since it is intrinsically difficult to generate an L-band SFS with the DPB configuration, the success of the cascaded dual-backward-pumped configuration for an L-band SFS presents many advantages. The ultra-high pumping efficiency and broadening linewidth L-band SFS can be achieved merely by changing the R_p and R_L ratios of the cascaded dual-backward-pumped configuration, as shown in Fig. 5. The 50.1% pumping efficiency of the proposed L-band SFS is higher and the 52.6-nm spectral linewidth is broader than those reported in Refs. 7 and 8 (36.1% and 40.8 nm in Ref. 7, 42.2% and 41.6 nm in Ref. 8). Although a recently reported L-band SFS exhibited a comparable spectral linewidth,[12] the pumping efficiency of 50.1% reported in this paper is much higher. Compared with the improved bidirectional pumping configuration reported in Ref. 13, the configuration presented here has the advantage of always providing a broad linewidth with various pump ratios, except that the pumping efficiency is also improved a little. The single-backward-pumped configuration with a section of unpumped fiber is also a good choice for generating a medium pumping efficiency and broadening the linewidth of an L-band SFS with the advantage of a simple one-pump configuration. We believe that the high-pumping-efficiency and broadening-linewidth L-band SFSs could be useful for applications in L-band DWDM device characterization and spectrum-sliced DWDM systems.

4 Conclusion

In conclusion, we have proposed and demonstrated an ultra-high-efficiency L-band SFS by using a cascaded dual-backward-pumped configuration to achieve a high output power and a broadening spectral linewidth with low power ripple characteristics and without using any external spectral filters. We found that the cascaded dual-backward-pumped configuration was successful in implementing the L-band SFS to provide an ultra-high-efficiency and a broadening linewidth as well. The characteristics of a 132.8-mW output power, a high 50.1% pumping conversion efficiency, a broadening 52.6-nm spectral linewidth, and a mean wavelength of 1578.2 nm were obtained. The dual-backward-pumped L-band SFS displays better characteristics than that of the dual-forward-pumped configuration and the bidirectional-pumped configuration. Such a flat, high-power ASE source is essential for L-band DWDM device characterization and spectrum-sliced DWDM systems.

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References

1. M. Zirngibl, C. R. Doerr, and L. W. Stulz, "Study of spectral slicing for local access applications," *IEEE Photon. Technol. Lett.* **8**, 721–723 (1996).
2. C. D. Su and L. A. Wang, "Multiwavelength fiber sources based on double-pass superfluorescent fiber sources," *J. Lightwave Technol.* **18**, 708–714 (2000).
3. P. F. Wysocki, M. J. F. Digonnet, B. Y. Kim, et al., "Characteristics of erbium-doped superfluorescent fiber sources for interferometric sensor applications," *J. Lightwave Technol.* **12**, 550–567 (1994).
4. L. A. Wang and C. D. Chen, "Stable and broadband Er-doped superfluorescent fiber sources using double pass backward configuration," *Electron. Lett.* **32**, 1815–1817 (1996).
5. S. C. Tsai, C. M. Lee, S. Hsu, and Y. K. Chen, "Characteristic comparison of single-pumped L-band erbium-doped fiber amplified spontaneous emission sources," *Opt. Quantum Electron.* **34**, 1111–1117 (2002).
6. S. Hsu, T. C. Liang, and Y. K. Chen, "Optimum configuration and design of L-band erbium-doped superfluorescent fiber source," *Jpn. J. Appl. Phys.* **41**, 3724–3729 (2002).
7. S. C. Tsai, T. C. Tsai, P. C. Law, and Y. K. Chen, "High-power flat L-band erbium-doped fiber ASE source using dual forward-pumping scheme," *Opt. Quantum Electron.* **35**, 161–167 (2003).
8. S.-C. Tsai, T.-C. Tsai, P.-C. Law, and Y.-K. Chen, "High pumping efficiency L-band erbium doped fiber ASE source using double pass bidirectional pumping configuration," *IEEE Photon. Technol. Lett.* **15**, 197–199 (2003).
9. OFS Specialty Photonics, "LRL erbium-doped fibers for L-band," http://www.specialtyphotonics.com/pdf/products/074_075.pdf.
10. OASIX v3.0 erbium-doped fiber devices simulation software, Lucent Technologies.
11. P. Z. Zatta and D. C. Hall, "Ultra-stability two-stage superfluorescent fiber source for fiber optics gyroscope," *Electron. Lett.* **38**, 406–408 (2002).
12. H. Wang, Y. G. Li, S. P. Chen, J. P. Zhu, and K. C. Lu, "Bandwidth broadening and efficiency enhancement of a double-pass forward L-band erbium-doped superfluorescent fibre source," *J. Opt. A, Pure Appl. Opt.* **8**, 897–902 (2006).
13. W. C. Huang, X. L. Wang, B. R. Zheng, H. Y. Xu, C. C. Ye, and Z. P. Cai, "A stable and wideband L-band erbium superfluorescent fiber source using improved bi-directional pumping configuration," *Opt. Express* **15**, 9778–9783 (2007).

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